Ocean Surface Wave Optical Roughness – Innovative Measurement and Modeling

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LONG-TERM GOALS

We are part of a multi-institutional research team funded by the ONR-sponsored Radiance in a Dynamic Ocean (RaDyO) program. The primary research goals of the program are to (1) examine time-dependent oceanic radiance distribution in relation to dynamic surface boundary layer (SBL) processes; (2) construct a radiance-based SBL model; (3) validate the model with field observations; and (4) investigate the feasibility of inverting the model to yield SBL conditions. The goals of our team are to contribute innovative measurements, analyses and models of the sea surface roughness at length scales as small as a millimeter. This characterization includes microscale and whitecap breaking waves.

The members of the research team are:

Michael Banner, School of Mathematics, UNSW, Sydney, Australia
Johannes Gemmrich, Physics and Astronomy, UVic, Victoria, Canada
Russel Morison, School of Mathematics, UNSW, Sydney, Australia
Howard Schultz, Computer Vision Laboratory, Computer Science Dept, U. Mass., Mass
Christopher Zappa, Lamont Doherty Earth Observatory, Palisades, NY

OBJECTIVES

Nonlinear interfacial roughness elements - sharp crested waves, breaking waves as well as the foam, subsurface bubbles and spray they produce, contribute substantially to the distortion of the optical transmission through the air-sea interface. These common surface roughness features occur on a wide range of length scales, from the dominant sea state down to capillary waves. Wave breaking signatures range from large whitecaps with their residual passive foam, down to the ubiquitous centimeter scale microscale breakers that do not entrain air. There is substantial complexity in the local wind-driven sea surface roughness microstructure, as is evident in the close range image shown in Figure 1. Traditional descriptors of sea surface roughness are scale-integrated statistical properties, such as significant wave height, mean squared slope (e.g. Cox and Munk, 1954) and breaking probability (e.g. Holthuijsen and Herbers, 1986). Subsequently, spectral characterisations of wave height, slope and curvature have been measured, providing a scale resolution into Fourier modes for these geometrical sea roughness parameters. More recently, measurements of whitecap crest length spectral density (e.g. Phillips et al, 2001, Gemmrich et al., 2008) and microscale breaker crest length spectral density (e.g. Jessup and Phadnis, 2005) have been reported.

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Our effort seeks to provide a more comprehensive description of the physical and optical roughness of the sea surface. We will achieve this by implementing a comprehensive sea surface roughness observational 'module' within the RADYO field program to provide optimal coverage of the

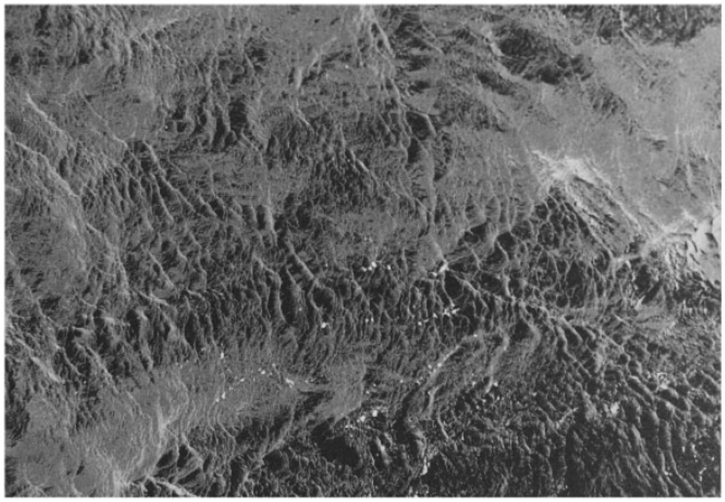

Figure 1. Image of the fine structure of the sea surface roughness taken during 12 m/sec winds (blowing from top left to lower right) and 3m significant wave height. Field of view is 4m x 2.6m.

fundamental optical distortion processes associated with the air-sea interface. Within our innovative complementary data gathering, analysis and modeling effort, we will pursue both spectral and phase-resolved perspectives. These will contribute directly towards refining the representation of surface wave distortion in present air-sea interfacial optical transmission models.

APPROACH

We build substantially on our accumulated expertise in sea surface processes and air-sea interaction. We are working within the larger team (listed above) measuring and characterizing the surface roughness. The group plans to contribute the following components to the primary sea surface roughness data gathering effort in RaDyO:

- polarization camera measurements of the sea surface slope topography, down to capillary wave scales, of an approximately 1m x 1m patch of the sea surface (see Figure 2), captured at video rates. [Schultz]

- co-located and synchronous orthogonal 75 Hz linear scanning laser altimeter data to provide spatio-temporal properties of the wave height field (resolved to O(0.5m) wavelengths) [Banner, Morison]

- high resolution video imagery to record whitecap data, from two cameras, close range and broad field [Gemmrich]

- fast response, infrared imagery to quantify properties of the microscale breakers, and surface layer kinematics and vorticity [Zappa]

- sonic anemometer to characterize the near-surface wind speed and wind stress [Zappa]

Our envisaged data analysis effort will include: detailed analyses of the slope field topography; laser altimeter wave height and large scale wave slope data; statistical distributions of whitecap crest length density in different scale bands of propagation speed and similarly for the microscale breakers, as functions of the wind speed/stress and the underlying dominant sea state. Our contributions to the

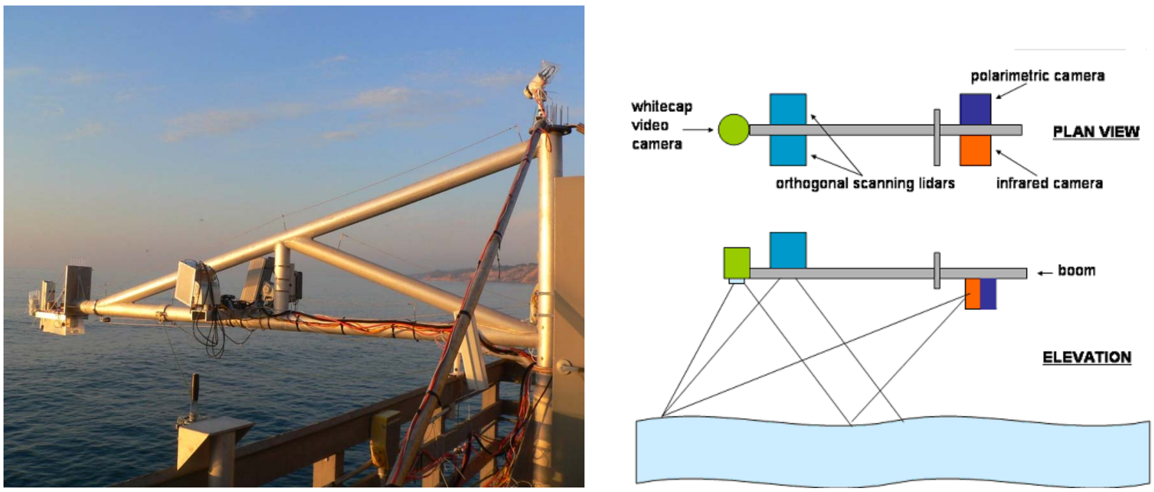

Figure 2. The left panel shows the instrumentation test set-up from the end of the Scripps Pier. The right panel shows a schematic of instrumentation packages deployed. The end of the boom was about 8m above the mean water level. The approximate field of view of the various instruments is shown. Another wide angle whitecap video camera was mounted well above the boom.

modeling effort will focus on using RaDyO data to refine the sea surface roughness transfer function. This comprises the representation of nonlinearity and breaking surface wave effects including bubbles, passive foam, active whitecap cover and spray, as well as microscale breakers.

WORK COMPLETED

Our effort in FY08 has been primarily in the detailed planning and execution of the suite of sea surface roughness measurements conducted at the Scripps Institution of Oceanography (SIO) from January 6-28, 2008 and the first RaDyO field experiment in the Santa Barbara channel during September 5-27, 2008.

In the Santa Barbara Channel experiment Dr. Howard Schultz has overall responsibility for the Narrow field-of-view Imaging Polarimeter (N-IPol) instrumentation and data processing. Dr. Chris Zappa installed the N-IPol on FLIP and collected data. The data processing and analysis will be a collaborative effort between Howard Schultz, Chris Zappa, Mike Banner, Russel Morison and Larry Pezzaniti (with Polaris Sensor Technologies).

With funding from an ONR DURIP award, we completed construction of the N-IPol[1]. We carried out validation tests of the N-IPol in the laboratory and at the (SIO) Pier Experiment (January 6-28, 2008). The results of the DURIP work and validation experiments were presented at the 2008 Ocean Sciences Meeting, and the 2008 SPIE Security and Defense conference.

We also built the data acquisition system consisting of three modules: 1) The sensor package containing a water tight enclosure, pan/tilt head, the N-IPol, CameraLink to fiber optic converters, an inertial measurement unit (IMU) for determining the precise orientation of the N-IPol and a digital thermistor; 2) a water resistant conduit containing power lines and fiber optic data lines; and 3) a portable 19" rack containing an interface box, the data acquisition computer, power supplies, and fiber optic to CameraLink converters. The system was designed for efficient deployment onboard FLIP. The system is assembled by mounting the enclosure to the pan/tilt head, connecting the conduit to the sensor package, and connecting the other end of the conduit to the interface box.

RESULTS

Figure 3 below shows the instrumentation deployed at the Scripps experiment. On the boom are two orthogonal line scanning lidars, synchronized for zero crosstalk developed by Banner and Morrison, a thermal imaging system developed by Zappa, a whitecap monitoring system developed by Gemmrich, and the N-IPol system. The various instruments were positioned on the boom so that their intersection point was within the common footprint of the polarimetric (Schultz), infrared (Zappa) and visible (Gemmrich) imagery cameras to measure small-scale surface roughness features and breaking waves. Zappa deployed his infrared/visible camera system (with blackbody target, a blackbody controller, a laser altimeter). He also deployed his environmental monitoring system (sonic anemometer, a Licor water vapor sensor, a Vaisala RH/T/P probe, a motion package, a pyranometer, and a pyrgeometer). Gemmrich deployed 2 video visible imagery cameras.

The primary purpose of the Scripps pier experiment was to prepare for the Santa Barbara and Hawaii experiments. To meet this goal we identified three tasks: 1) test the new N-IPol recently delivered by Polaris Sensor Technologies, 2) work out the calibration procedure for the N-IPol, and 3) test the synchronization procedures between the infrared imager and the N-IPol data acquisition systems. We were able to recover surface slopes with the new N-IPol instrument and synchronize the Infrared and N-IPol instruments. Figure 2 shows a sample intensity image, and x- and y-slope images from the N-IPol with a co-located frame from infrared imager. There were a few N-IPol calibration issues related to determining the registration and relative sensitivity of the four internal CCD images. These calibration issues were resolved and incorporated in to the Santa Barbara channel experimental procedures.

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[1] DURIP grant "Equipment in Support for Polarimetric Imaging," PI: Dr. Howard Schultz, Award Number: N00014-07-1-0731

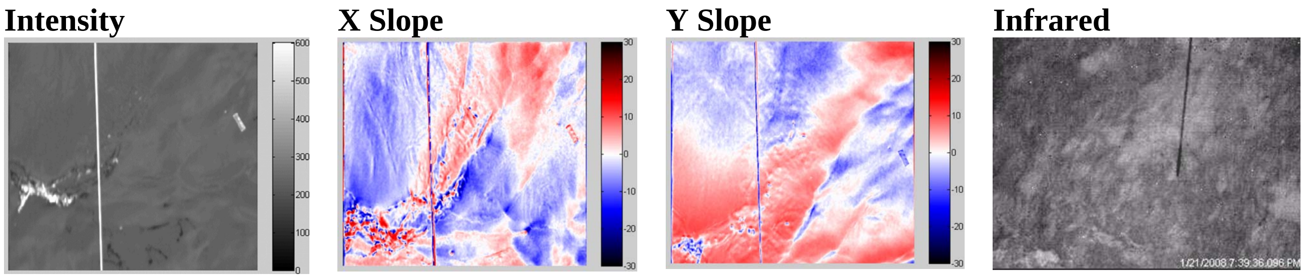

Figure 3. A sample of an intensity image, x and y-slope images and an infrared image. The line in the center is a cable extending from the boom to the water surface.

IMPACT/APPLICATIONS

Emerging optical remote sensing techniques based on polarimetry have the potential to provide high spatial and temporal resolution topographic information about ocean surface waves. Our recent work within the RaDyO program and the DURIP award “Equipment in Support for Polarimetric Imaging” (N00014-07-1-0731) has developed an imaging polarimeter that successfully recovers two-dimensional slope fields at up to 60 Hz frame rates of very short gravity wind waves down to capillary waves.

When applied to oceanography and fluid mechanics problems, polarimetric imaging techniques have the potential of significantly improving the ability of investigators to study surface overturning and bubble production associated with open ocean wave breaking are the major drivers of upper ocean turbulence production and mixing, and dissipation of wave energy. In addition, breaking waves generate sea spray and droplets, and enhance microwave backscatter and underwater ambient noise generation.

In principle the Polarimetric Slope Sensing technique can be applied from vantage points above and below the water surface. In the RaDyO program the focus is on using a down looking imaging polarimeter. However, several unique applications exist for deploying a submerged, up looking, imaging polarimeter. An important facet of our long term goals is to determine the feasibility of using a submerged imaging polarimeter to recover the surface slope field. The advantages to observing the surface from below includes, reduced interference of the surface wind and wave field from the observation platform, and an increase in the amount of light energy reaching the sensor.

A submerged, up looking polarimeter, may enable imaging the surface environment from a subsurface sensor. This application is based on four-step process for removing image distortion caused by surface waves (see PATENTS below). The first step employs an imaging polarimeter to measure the polarimetric radiance of down-welling light from a vantage point below the water surface. The system then computes the 2-dimensional surface slope field from the polarization change caused by light refracting through the water surface. In the third step, Snell’s law is used to compute the change in orientation of the refracted light rays. Finally, the system uses the change in orientation to remove the image distortion cause by light refracting through the wavy air/water interface. After applying this process, the resulting images have the appearance of being taken through a flat water surface. We therefore refer to this process as optical flattening.

The optical environment associated with observing transmitted light is significantly different from observing reflected light. The methods developed for observing reflected light cannot be directly applied to an up looking configuration. Consequently, additional studies are needed to extend the Polarimetric Slope Sensing technique to an up looking configuration.

RELATED PROJECTS

In FY07 we received a DURIP award ("Equipment in Support for Polarimetric Imaging," PI: Dr. Howard Schultz, Award Number: N00014-07-1-0731) to develop an operational, field-deployable polarimetric imaging system for recovering the two-dimensional time-varying slope field of short gravity waves at video frame rates. The instrumentation developed through this DURIP award is deployed in our RaDyO experiments.

At the University of Massachusetts we are developing a new passive optical technique based on polarimetry. Conventional optical remote sensing techniques rely on light amplitude and frequency to carry information about the scattering surface. The polarimetric method exploits these properties, as well as the polarization properties of light to sense information about the scattering media. When the polarimetric properties of light are included, the increased information about the scattering media is striking. We demonstrated in a recent exploratory experiment that the two-dimensional slope field of short gravity wave can be recovered from a distance without interfering with the fluid dynamics of the air or water.

Nondestructive remote sensing methods for measuring the dynamics of ocean surface waves are critical to many important oceanographic and fluid mechanics research topics. Understanding how energy is transferred from the atmosphere to the ocean, the growth and decay of waves, and gas exchange are a few examples of research topics that depend on a good knowledge of the ocean surface dynamics. Investigators have often built instruments that exploit the scattering properties of light to sense the air-sea interface. Some examples of light sensing devices include stereo photography, sun glint photography, specular surface stereo, laser slope gauges, laser profiling, and color table slope gauges. The problem with these methods has been extracting sufficient information from passive measurements and constructing a nondestructive instrument for active devices.

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J. Larry Pezzaniti, David Chenault, Mike Roche, John Reinhart, Joseph P. Pezzaniti, and Howard Schultz (2008) "Four Camera Complete Stokes Imaging Polarimeter," SPIE Paper # 6972-19 Polarization: Measurement, Analysis, and Remote Sensing VIII, SPIE Defense and Security, Orlando, FL March 17-20. [Published, Refereed]

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PATENTS

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